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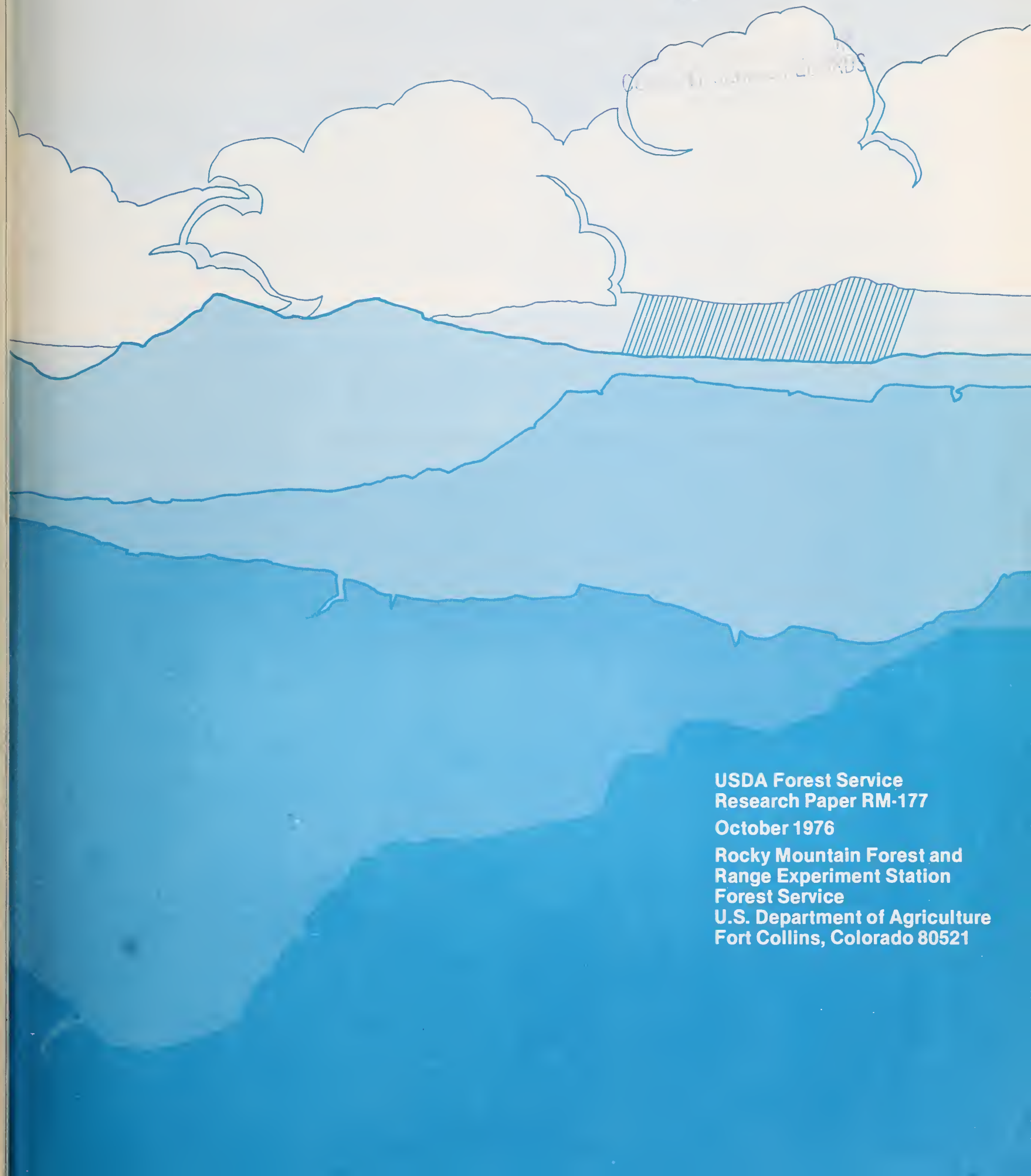
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# Fire Danger Rating Network Density

Rudy M. King and R. William Furman

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### Abstract

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Conventional statistical techniques are used to answer the question, "What is the necessary station density for a fire danger network?" The Burning Index of the National Fire-Danger Rating System is used as an indicator of fire danger. Results are presented as station spacing in tabular form for each of six regions in the western United States.

**Keywords:** Forest fire control, forest fire danger rating.



# Fire Danger Rating Network Density

Rudy M. King, Mathematical Statistician  
and

R. William Furman, Research Meteorologist  
Rocky Mountain Forest and Range Experiment Station<sup>1</sup>

## Introduction

It has been a policy of fire managers to measure fire danger on the worst sites and at the worst time of day. Typically, the worst sites are on the south slope at mid-elevation, and the fire danger is at its worst in mid-afternoon (Hayes 1944). These measurements are then used in a fire-danger rating system to establish a level of preparedness to suppress fires that may occur under the "average worst" situations.

## Problem and Objectives

The problem to be considered is: How many fire weather stations are necessary to monitor fire danger adequately? The criterion we used was that a system of stations should be able to measure, at a predetermined level of precision, the "average worst" fire danger conditions. To represent fire danger conditions in this study, we used the Burning Index in the National Fire Danger Rating System (Deeming et al. 1972).

The objective of this study was to estimate the density of fire-danger stations necessary to satisfy the above criterion for six western U.S. geographic regions that were assumed to have "relatively homogeneous" properties (spatial mean and variance) of the Burning Index. Then, to provide somewhat more meaningful numbers, the station densities for the different regions were expressed as station spacings.

## Pertinent Literature

In 1937, Gisborne (1937) set forth what he considered to be general principles of rating fire danger. He specifically mentioned the lack of guidelines for determining the number of stations necessary to monitor fire danger over an area. He also suggested that the measurements of fire danger taken represent the whole forest property. However, he made no suggestions as to how this was to be done. We know today that the natural

variability of fire danger in a watershed makes Gisborne's philosophy impractical.

Morris (1939) suggested that preparedness should be based on what he defined as the "worst probable" condition. Although the quantitative definition of "worst probable" or "average worst" has changed over the years, the concept is still the same: to be prepared to take whatever action may be required.

Morris (1940) suggested a quantitative approach to the problem of determining the number of fire danger stations needed. He divided Washington-Oregon into major drainages, and determined for each drainage the station spacing required for a precision level of 5 miles per hour (mi/h) for wind and 2.5% for minimum fuel moisture index in 99 out of 100 cases. Although he showed that there should be a different station density on mountain tops than at other locations for the given levels of precision, the differences were not consistent. Mountain-top stations required a more dense network than lower locations for measuring windspeed, but a less dense network for fuel moisture.

In the longleaf pine region of the Southeast, where topographic conditions are not so varied, Knorr (1942) determined that a single fire danger station per Ranger District (approximately 400,000 acres) was adequate to monitor the variation in fire danger. He found that fuel-moisture measurements were not different among the seven stations in the study. Differences were noted, however, in wind velocity and rate-of-spread index. One of the alternatives he recommended was to monitor the sites where fire hazard was "worse-than-average," to be prepared for severe fires. No criteria were given to determine the size of the area that could be covered by a single station.

Hayes (1944) proposed that, under the conditions prevailing in the Priest River Experimental Forest in northern Idaho, a single measurement of fire danger taken daily at noon at either a valley-bottom or a south-slope station is adequate for rating of fire danger. However, the area that the single station was to represent was not considered. Tucker (1960) recommended that stations be located such that the elements measured will be representative of the area, but quantitative guidelines were proposed for the density of stations necessary in a network, or what the dimensions of the area represented would be.

<sup>1</sup>Central headquarters is maintained at Fort Collins, in cooperation with Colorado State University.

## Development of the Methodology

The task was to estimate the density of stations needed for a specified geographic region with relatively uniform fire weather. To partition the country into areas of relative homogeneity, we used the fire-climate regions suggested by Schroeder and Buck (1970) (fig. 1).



Figure 1.—Homogeneous fire-climate regions (after Schroeder and Buck 1970).

The index used to express fire danger in this paper is the Burning Index of the National Fire-Danger Rating System (NFDRS) (Deeming et al. 1972). This index of fire intensity responds to weather and available fuels. The spatial variability of fuels was eliminated by considering the fuel complex constant throughout each region. The Burning Index then becomes a weather index that reflects the fire hazard on a scale of 1 to 100. The spatial variability of this Index was used to determine the station density.

The basic idea is to estimate the spatial mean Burning Index for a given day for stations in an assumed "relatively homogeneous" geographic region. The more diversity found among the actual stations sampled, the larger will be the number

of required stations (or the greater the station density) to predict fire danger at a specified precision level. Thus a station density should be adopted which will adequately sample the range of Burning Index values found over the region.

The data used were the fire weather observations collected by land management agencies for use in determining fire hazard. These data for stations from all over the United States are available in a computerized data library stored on the USDA computer in Fort Collins, Colorado (Furman and Brink 1975). For each day sampled, the Burning Index was computed and used as the random variable.

For this study, more than 300 fire-danger stations were sampled. Because of the lack of available stations on south-facing mid-elevation slopes, we sampled stations on mountain-top and high-elevation sites. It was assumed that a sample of these stations would give the best measure of the spatial variation about the mean for the south-facing mid-elevation slopes in a given homogeneous region. We believe this assumption to be an acceptable first approximation because of the unclear differences in station density found by Morris (1940), discussed earlier, and the graphs of forest-fire behavior presented by Hayes (1944). Those graphs show that the difference in forest-fire behavior between mountain top and mid-elevation is not as large as between mid-elevation and valley bottom in the middle of the afternoon, the observation time used in this study. The tolerable amount of spatial variation about the area mean is the determining factor in estimating the station density required to achieve a given level of precision.

It should be noted that this estimate of variance is low because of the lack of independence among sample stations relatively near one another. The estimate of spatial variance would have been increased by an estimate of the covariance between such stations, but the correlation-distance relationship in terms of Burning Index was too irregular to be adequately modeled. Thus the biased estimate was used. The significance of ignoring this bias is that the results presented must be considered as strictly the **upper limit** of station spacing needed to achieve the desired precision.

The Burning Index was calculated for every third day in the fire-danger season for a sample of stations in a given region. Such a sample should effectively measure the variability of changing conditions during the fire-danger season, yet to a large extent remove any day-to-day dependence and thus achieve a relatively independent sample of days. In each region on any given sampling day, a minimum of 30 observations of the Burning Index was necessary for that day to be included in calculations of the spatial mean fire danger.



The spatial mean and variance were estimated for each of k days sampled. Then, according to Cochran (1963, p. 75-76), the following probability statement applies:

$$\Pr (|\bar{y} - \bar{Y}| \geq d) = \alpha \quad [1]$$

where  
 $\alpha$  is a small specified probability level,  
 $\bar{y}$  is the estimate of the spatial mean for a given day,  
 $\bar{Y}$  is the population spatial mean, and  
d is the specified tolerable amount of variation about the mean.

Assuming the sample mean is normally distributed, inversion of eq. [1] leads to an estimate of the required station density, n:

$$n = t^2 S^2 / d^2 \quad [2]$$

where  
t is the value of the t distribution at significance level  $\alpha = 0.05$ , and  
 $S^2$  is the estimate of spatial variance.

With values of n estimated for each of k days sampled, we now have sample estimates of the station density needed to maintain an arbitrary level of precision throughout the fire season. The range of these estimates was generally quite large. We concluded the larger estimates represent ex-

treme variation that could not be measured economically, and therefore chose to maintain a precision level over only a fraction of the fire season. That decision involves an arbitrary choice as to what percentage of the fire season to cover. We then take as the minimum required station density that estimate which is as large or larger than the chosen percentage of the ranked estimates.

## Application of Results

For each of the western regions in Schroeder and Buck (1970), the maximum station spacing was estimated for a tolerable error of  $d = \pm 1$  Burning Index unit for a given percentage of days and for NFDRS fuel models<sup>2</sup> (Deeming et al. 1972) selected as appropriate to the region (table 1). This tabular representation assumes that the estimated density reflects the number of uniformly spaced stations needed to monitor fire danger in the area protected. Station density was converted to spacing by assuming each station monitors a circular area about itself, and solving for the diameter of the circle to obtain the maximum spacing between stations.

<sup>2</sup>A fuel model is a simulated fuel complex for which all the fuel descriptions required for the solution of the fire spread model have been specified.

Table 1.--Estimated maximum station spacing in miles for an allowable margin of error<sup>1</sup> about the area for mean Burning Index of  $\pm 1$ . Results are for selected fuel models<sup>2</sup> for a percentage (P) of the days in the fire season<sup>3</sup>

FIRE-CLIMATE REGION 2				FIRE-CLIMATE REGION 3				FIRE-CLIMATE REGION 4						
Fuel Model				Fuel Model				Fuel Model						
P	A	C	I	P	A	B	C	P	A	C	D	G	H	I
90	11	22	9	90	5	6	14	90	12	27	20	19	40	11
80	14	25	11	80	6	6	15	80	16	30	22	21	46	13
70	16	28	12	70	6	7	16	70	19	33	24	23	49	13

FIRE-CLIMATE REGION 5			FIRE-CLIMATE REGION 6				FIRE-CLIMATE REGION 7			
Fuel Model			Fuel Model				Fuel Model			
P	A	C	P	A	D	H	P	A	B	C
90	5	14	90	9	15	31	90	5	7	17
80	6	17	80	11	18	36	80	7	8	18
70	7	19	70	13	19	40	70	9	9	20

<sup>1</sup>To achieve a margin of error (d) other than  $\pm 1$ , multiply the tabled value by d.

<sup>2</sup>Figures for fuel model A are based on mean spread component.

<sup>3</sup>Fire season is June to September except in Fire-Climate region 7, which is May to September.

To apply table 1, the user must first decide which NFDRS fuel model is most appropriate for his particular fire-climate area. This fuel model will determine the column of the sub-table from which he should draw his station spacing estimate. Then, by varying the percentage-of-days criteria, he can find an estimated maximum station spacing that will give him sufficient precision and economy for an error of  $\pm 1$ .

If an error in the area average larger than  $\pm 1$  is tolerable, he may adjust the station spacing by multiplying the table value by the tolerable error. For instance, suppose a user in fire-climate region 6 wanted to use NFDRS fuel model D. Initially he decides that he can tolerate an error about the mean of 3, and he wants this error to be safe 80% of the fire season. The table tells him that for an error of 1, his stations can be located no farther apart than 18 miles. Hence, for an allowable error of 3, his station spacing can be  $18 \times 3 = 54$  miles. If this spacing is still too stringent, he must relax one or both of his criteria to the point that he obtains a spacing he can economically tolerate. Conversely, if he can tolerate a smaller spacing he can tighten his criteria to gain more precision or cover a larger portion of the fire season. In either case, he should be able to design a network with a good idea of what level of precision he is likely to receive.

Table 1 can also be used to estimate the level of precision currently being attained by an existing system of stations. By estimating the average station spacing in his present system, a user can then solve backward through the appropriate table to obtain estimates of the error present for different percentages of the fire season covered. For instance, continuing the above example, suppose a user estimates his station spacing to be 40 miles. Dividing the existing spacing by the table value for a given percentage coverage he will determine the current error around the areal mean. From the table at the 80% coverage level for model D, the spacing for an error of 1 is 18 miles. Since the existing network has a spacing of 40 miles, the error about the mean for 80% of the time is  $40/18 = 2.2$  BI units. For 90% of the time, the error about the mean is about  $40/15 = 2.7$  units.

### Summary

We have used conventional statistical techniques to answer the question "What is the necessary station density for a fire danger network?" The Burning Index of the National Fire-Danger Rating System was used as an indicator of fire danger, and the results were presented as station spacing, with a different table for each of six regions in the western United States.

Several assumptions were necessary to achieve these results. First, it was assumed that the fire-danger regions delineated by Schroeder and Buck (1970) were in fact homogeneous in fire danger. Secondly, it was assumed that the spatial variations of the Burning Index sampled from lookouts and high-elevation sites were nearly the same as those for the "average worst" sites. Thirdly, the biased estimate of spatial variance was used, since no covariance structure could be found among the stations to correct the variance. Using this biased estimate had the effect of making the final numbers upper limits of station spacings in miles necessary to estimate the areal mean of the Burning Index with a certain precision a specified amount of time. These station spacings should provide approximate guidelines for planning fire-danger station network densities.

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